SUMMARY

DEFINITION OF ULTIMATE ATTAINABLE SPATIAL RESOLUTION

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This session was concerned with trying to identify some of the basic principles and limitations of ultra-high spatial resolution analytical electron microscopy (AEM) techniques. Most of the AEM attempts at attaining ultimate spatial resolution utilize electron-energy-loss (EELS) signals, although some work has been done with energy-dispersive X-ray analysis (EDSx) and Auger electron spectroscopy (AES). Almost all of the ultra-high spatial resolution studies performed in the past decade have been done utilizing the dedicated STEM, although the consensus of the 1978 Cornell Workshop indicated that "the dedicated STEM consisting only of probe-forming optics and appropriate detectors did not represent a suitable instrument for most experimental purposes as it was too restrictive" [Ultramicroscopy, 3 (1979) 359]. Ironically, no fundamental improvements to the basic STEM column design or the probe-forming electron lenses have been implemented in the past decade in order to increase spatial resolution.

Some advances in instrumentation have made necessary improvements in order to approach the ultimate spatial resolution. As projected in the 1978 Cornell workshop, parallel recording for acquiring EELS data has become an integral part of high resolution data-acquisition equipment. Parallel recording systems are now in use in many laboratories throughout the world. The processing of several AEM signals simultaneously was also projected by the 1978 Cornell workshop to be an integral part of expanding the potential of high spatial resolution work. In the last decade, the use of ever faster

electronics has extended the acquisition of simultaneous AEM signals to include coincidence counting techniques whereby different AEM signals are correlated (in time) in the hope of isolating individual scattering events. Finally, advances in computer technology have made sophisticated data acquisition and data processing fast, convenient and inexpensive.

A succinct definition of spatial resolution is required to quantify the ultimate spatial resolution attainable in AEM. Several criteria, as pointed out by H. Kohl, have been used, and they are: (1) point-to-point resolution which defines the minimum distance between two separable details in an (aperiodic) electron micrograph as the resolution ; (2) edge resolution which defines the distance between the 20% and 80% points in the intensity profile of a line scan taken across a sharp interface (in an image or energy filtered image) as the resolution ; (3) the contrast transfer function which defines the resolution as that length associated with the cut-off $\underline{k}$-vector determined from a diffractogram of an image of a thin (single scatterer) target ; (4) the cross-correlation peak resolution which defines the width of the cross-correlation peak between two similar images of the identical sample as the resolution. What is evident is that different definitions of ultimate spatial resolution are currently attached to the distinct physical structures under experimental observation. Unification of these definitions will be required to quantify future work.

Electron-energy-loss spectroscopy has been widely used to obtain ultrahigh spatial resolution maps of chemical and electronic states. Astounding progress has been made in forming chemical maps in STEM since the last Cornell workshop largely due to parallel EELS detectors, which increase the collection efficiency of the energy-loss system by 2 or more orders of magnitude. This also allows for the observation of beam damageable materials. The ultimate test of an AEM technique is the identification and isolation of single atomic chemical species in a specimen. In EELS, the excitations in the core-loss spectra, which are generally in the greater

than 100 eV energy-loss range, are considered to be sufficiently spatially localized to attempt single-atom inelastic imaging. This has been nearly accomplished whereby 1-2 atoms of U or Tb can be differentiated from the background in inelastic images obtained by utilizing cross-correlation techniques, the annular dark field (ADF) and energy-filtered images formed in STEM. There appears to be less than 2 Å of spatial resolution degradation in the inelastic images formed using inelastic (100 eV energy loss) electrons as compared to ADF images, indicating that near-atomic-resolution chemical mapping is becoming a reality.

Although at the last Cornell workshop "it was felt that EELS in this region (The low-loss or 0-50 eV range) could not be used as a practical method at very high spatial resolution (less than 50-100 Å)" [Ultramicroscopy 3 (1979) 429], recent results on the inelastic imaging of plasmons and surface plasmons in STEM have revealed that extremely high spatial resolution is attainable. Recent studies of misfit dislocations in III-V semiconductors by P. Batson have also shown that extremely high spatial resolution information may be attained from the EELS spectrum near the band-gap energy. Further, the information gained from the low-loss spectrum measurements correlates well with observation of electron energy core-loss data. The advantage in utilizing the low-loss spectrum is that the signal may be several orders of magnitude more intense than the core-loss signal.

Energy-dispersive X-ray (EDX) spectra from STEM probes scanned across segregation grain boundaries are used to form composition profiles. This technique has become the standard for assessing the lateral spatial resolution of the EDX techniques. Since the high-angle elastic scattering of incident electrons spreads the beam as $t^{3/2}$ (where t is the film thickness), thick samples produce some lateral spatial resolution degradation in the EDX composition profiles relative to the profiles obtained with EELS. This has been confirmed experimentally. Thus it seems unlikely that EDX signals will be utilized effectively in ultimate spatial resolution studies. Auger

electron spectroscopy studies have also been performed in STEM whereby 80 Å lateral spatial resolution has been attained.

Ultimate spatial resolution, unfortunately, cannot be defined without regard to sample composition. Since all materials are beam damageable to some degree, attention must be paid to the damage dose while acquiring spectra. Further, the samples may not only be dose sensitive, but may also be dose-rate sensitive. One commonly used technique to combat radiation damage is to cool the specimen, thereby reducting effects which are deleterious to the acquisition of high spatial resolution spectra.

Since the last Cornell workshop, great strides towards the ultra-high spatial resolution mapping of chemical and electronic states has been made. Most of the progress has resulted from improved data acquisition and data processing techniques. Relatively few, if any, fundamental instrumentation improvements have been advanced in the last decade that were not already in development at the time of the last meeting. Most, if not all, ultra-high spatial resolution studies take place in a dedicated STEM operating near 100 keV. The next decade must see fundamental advances in the basic probe-forming instrument in order to push towards ultimate spatial resolution. New electron sources must be developed which are brighter and more achromatic. Further, novel electron lens configurations, such as that being implemented by VG and Arizona State University in the MIDAS project, are necessary in order to more efficiently extract the AEM signals. Finally, the convergence of the surface science instrument with the analytic electron microscope should provide a fertile environment for the acquisition of ultra-high lateral surface spatial resolution information.